Pine (*Pinus sylvestris L.*) Penetration towards the Head of the Handölan Valley: Recent Reversal of Long-Term Retrogressional Trend –Contrasting Responses to Climate Change of Tree-and Forest Line.

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Abstract— *With a climate-change perspective, this study focuses on the recent history and performance of the much separated pine (Pinus sylvestris L.) tree and forest lines in a mountain valley in the southern Swedish Scandes. Historical records define quite accurately these "lines" by the early 20th century and mid-1970s. Their subsequent dynamic performances have been surveyed up to the present day. Both lines are currently positioned within the subalpine mountain birch forest belt (Betula pubescens ssp. czerepanovii). Consequently, their past, present and future changes rely on the evolution of the birch forest matrix. Between the early 20th century and the mid-1970s, the position of the pine forest- and tree lines remained fairly stable. Conspicuously, the forest line population densified in accord with early-20th century climate warming, although with a stagnant position. In great contrast, the tree line, i.e. scattered solitary, fast-growing and vigorous trees, has shifted up-valley 135 m through the birch forest belt to a position about 12 km south of the position by the mid-1970s. It is hypothesized that the vast separation of forest- and tree line relates to the presence of the subalpine birch forest belt. This contention is supported by vigorous growth of outlier pine trees, predominantly in birch forest gaps and a treeline gradually rising towards the south in the valley. Accordingly, it is hypothesized that, with present-day climatic conditions, the potential pine forest line is much south (and higher) of its present position within the competing birch forest belt. In the case of future climate warming, this forest range is anticipated to be realized. That would be a return to the situation during the early- and mid- Holocene, when pine dominated the upper tree line ecotone and the birch belt was poorly developed.*

Keywords— Tree line, forest line, Pinus sylvestris, climate change, subalpine birch forest.

I. INTRODUCTION

On long- and short time scales, cold-marginal treeline stands, ultimately constrained by heat deficiency, may perform as sensitive biological indicators of climate change and variability (Kullman 1998; Holtmeier 2003; Körner 2007; Kharuk et al. 2009; Kullman & Öberg 2009). However, on local spatial scales, treeline responses to altered climatic conditions are modulated by topoclimatic, biotic and landuse factors as well as plant cover legacies (Kullman & Öberg 2009; Leonelli et al. 2011; Holtmeier & Broll 2012).

A fundamental response dichotomy may concern the treeline[1] and forest line[2], i.e. the uppermost peripheral single trees and the fringe of more or less closed forest, respectively (cf. Kullman 2010, 2014a). In the Scandes, extensive regional-scale elevational treeline upshifts of different species in close accord with post-Little Ice Age warming (Kullman & Öberg 2009) are not paralleled by analogously large advance of closed-canopy forest (Kullman1990, 2010, 2014a, b; Hofgaard et al. 2013; Rannow 2013). Despite substantial warming during the past 100 years, tree and forest stands have not become re-established at those high elevations were they grew during earlier warmer-than-present epochs of the Holocene, e.g. the Medieval Climate Optimum, around 1000 years ago and finally became extirpated during the subsequent Little Ice Age climate cooling (Kullman 2015b).

Most available data indicate that the treelines of all species have been positionally more compliant with climate change and variability than their forest lines (Kullman & Öberg 2009).The resilience of the forest line versus treeline was anticipated by early botanical explorers, stressing relatively subdued responses of the former and its great spatial variability in areas with virtually the same climate and more contiguous tree lines (Smith 1920; Enquist 1933; Kvamme 1993; Körner 2007). In this context it may be pertinent to reconsider a view flourishing among botanists working with treelines in the European Alps during the early 20th century claiming that a site where a solitary tree can grow, can also support the existence of closed forest (cf. Scharfetter 1938; Schiechtl 1967). This unvalidated contention has a particular relevance today, in connection with efforts to interprete "early warning" signs of changed balance between forest and alpine tundra in a hypothetical case of

future climate warming. Currently, pine trees are commonly becoming established far beyond the limit of closed-canopy pine forest (Kullman & Öberg 2009; Kullman 2010, 2014b). A pertinent question is whether these new tree line markers also represent today´s potential limit of forest growth, although not yet realized due to lack of seed and dispersal constraints, imposed primarily by a dense and fairly stable birch forest belt (cf. Blűthgen 1960; Shiyatov 1993; Kullman 2010, 2014a, Holtmeier & Broll 2011).

Still, the enigma concerning differential nature and performance of tree and forest lines constitutes a caveat in the context of environmental monitoring (Kullman 2015c) and modelling future landscape ecological responses to climate change.

Models of the latter kind commonly envisage extensive forest encroachment on the alpine tundra, with profound consequences for flora, fauna, carbon cycling and radiation balance (Moen et al. 2004; ACIA 2005; Bernes 2007; Kaplan & New 2006). However, it has been pointed out that models projecting rapid forest expansion (e.g. Moen et al. 2004) over the alpine tundra are overstated and poorly supported by observational data (Moen & Lyngstad 2003; Rössler et al. 2008; Kullman 1986, 2009, 2014a; Hofgaard et al. 2013). Moreover, a sluggish pine forest advance up to the present, despite substantial climate warming, represents a climate-distribution disequilibrium state and appears as a more general option in the north (Davis 1989; Campbell & McAndrews 1993; Zackrisson et al. 1995; Hiller et al 2001; Holtmeier et al. 2003; Körner 2005; Payette 2007; MacDonald 2010; Paus 2013; Kullman 2014a). In Scandinavia and adjacent regions, this mechanism seems merely conditioned by dispersal constraints, related to the presence of a dense subalpine birch forest belt, functioning as a filter between the upper pine forest and the alpine tundra (Holtmeier 1974; Shiyatov 2003; Kullman 2010, 2015). Disequilibrium performance, in general, stands out as a particularly challenging aspect for the interpretation of tree and forest history at landscape and population scales. Proper forecasting of future biogeographic dynamics in general and treeline dynamics in particular, under prescribed climatic regimes in mountain regions, rely on a deeper understanding of this issue (cf. Zackrisson et al. 1995; Johnstone & Chapin 2003; Caccianiga & Payette 2006; Svenning & Sandel 2013; Normand et al. 2013).

Against the background outlined above, the present paper seeks to highlight the discrepancy between pine (*Pinus sylvestris* L.) treeline and forest line advance during the past 100 years or so. The reason for focusing on pine in particular is the fact that this species dominated the treeline ecotone during the earliest and warmest part of the Holocene (Kullman 2013). Moreover, pine is the only tree species in the region which reproduces solely by seed, which facilitates interpretation of stand history, since one has not to consider responses of a bank of old-growth krummholz specimens above the treeline. In addition, discernible onset of pine forest encroachment on alpine tundra during recent relatively warm decades is recorded in the southernmost Swedish Scandes (Kullman 2010, 2014b). This course of change coincided with and was conditional on recession of the competing birch forest belt, in response to earlier and more complete snow melt, which imposed drier soils (Kullman 2014b). Therefore it is reasonable to assume that in a substantially warmer future, pine will in due time regain some of the territory lost during the course of gradual Holocene climate cooling (Kullman 2013, 2015b). Accordingly, it may be hypothesized that a currently extended range of solitary pine trees may constitute an early positional indication and source of an extended cold limit of pine forest stands in a possibly warmer future. The realism of this option is tested with this field study of tree growth performance, carried out in a long mountain valley, trending towards large expanses of alpine tundra. This valley is particularly well-researched with respect to past and recent treeline and forest line history, which facilitates interpretation (Lundqvist 1969; Bergman et al. 2005; Kullman & Kjällgren 2006; Öberg & Kullman 2011; Kullman 2014a and literature cited therein).

II. STUDY AREA

The study area lingers along the Handölan River in the bottom of the north-south trending mountain valley (690-830 m a.s.l.), between closed spruce and pine forest at lower elevations and mountain birch forest (*Betula pubescens* ssp. *czerepanovii*) higher upslope (Fig. 1). Surrounding mountain peaks reach 1400-1500 m a.s.l. The alpine treeline on these mountain slopes is generally formed by mountain birch, 900-1100 m a.s.l. The study takes its start fairly close to the mouth of the valley, 63° 15´ N; 12° 25´E, about 3 km south of the village Handöl, where the southernmost outpost of pine forest has prevailed for more than a century (Kullman 1986; 2014a). It extends about further 20 km southwards to 63° 05´ N; 12°25´ E.

The concerned valley has a long history as grazing ground for semi-domesticated reindeer. Associated activities by the indigenous reindeer herding Sami people have locally caused some thinning of the birch forest.

During the period 1901-2013 summer (J, J, A) and winter (D, J, F) temperatures in the region increased by 1.4°C and 1.2°C, respectively. Precipitation increased by 5-10 % over virtually the same period of time. These data, derived from the Swedish

Meteorological and Hydrological Institute and refer to the station Storlien/Visjövalen, 642 m a.s.l., located about 20-25 km the northwest (Kullman 2015c).

More detailed accounts of the study area, its geology, climate, landforms, human impact, Holocene and recent vegetation history are provided by different sources (Lundqvist 1969; Borgström1979a,b; Kullman 1983;Kullman & Öberg 2009; Kullman 2014a).

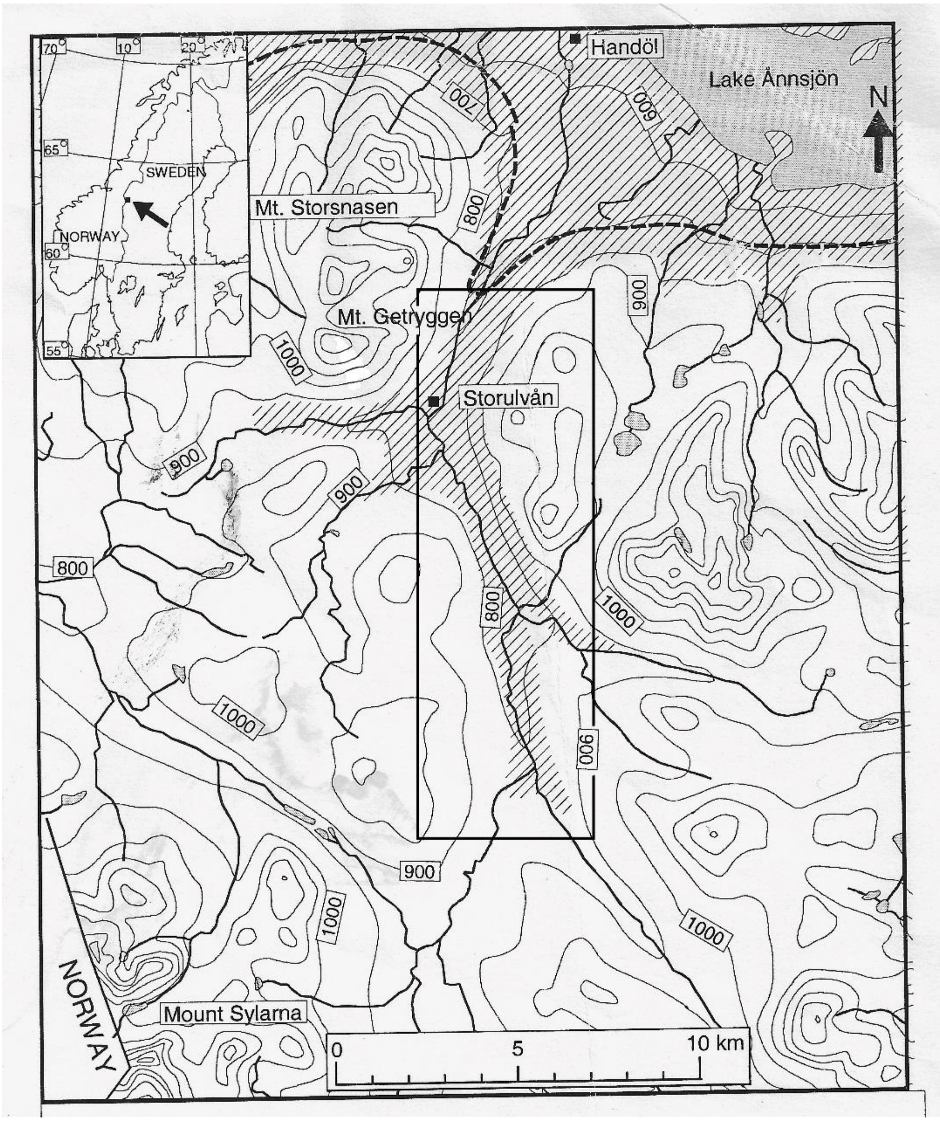

FIGURE 1. LOCATION MAP SHOWING THE STUDY AREA. THE HATCHED AREA DENOTES THE COVER OF MOUNTAIN BIRCH FOREST FRINGING THE TREELESS ALPINE TUNDRA, WHILE THE DASHED LINE INDICATES THE DISTRIBUTION LIMIT OF CLOSED-CANOPY PINE FOREST STANDS.

III. METHODS

Extensive and systematic field surveys during virtually all seasons of the year (1973-2015) enabled detailed mapping of the pine distribution (seedlings, saplings and trees) and its continual extension towards the valley head during recent decades.

Tree ages of mature pine individuals were estimated by coring as close to the ground level as possible. Saplings were aged by counting branch whorls and their scars. All recovered specimens were photographed and tallied with respect to height and vitality.

Altitudes (m a.s.l.) and geographical positions of recovered pines were documented by a GPS navigator (Garmin 60CS), routinely calibrated against distinct points on the topographical map. Reported altitudes are rounded off to the nearest 5 m.

IV. RESULTS AND DISCUSSION

The pine forest line prevailing by the early 20th century, on both sides of the Handölan River, has not significantly changed position during the past 100 years or so, as evident from old photographic and documentary records (Fig. 2 and 3) in combination with modern age structure analyses of extant trees(Andersson 1903; Kullman 1986, 2005; 2014a, 2015a,b). However within the historical limit, substantial infilling, crown expansion and vitalization took place over this period, when about 60 % of today´s trees became established (Kullman 1986; 2004).

FIGURE 2. THE CURRENT PINE FOREST LINE IN THE HANDÖLAN VALLEY, 685-690 m a.s.l. (63° 15´N; 12° 25´E). THE FOREST LINE HAS REMAINED POSITIONALLY STABLE HERE FOR A CENTURY OR SO. ABOUT 60 % OF THE EXTANT TREES BECAME ESTABLISHED DURING THE PAST 100 YEARS, APPARENTLY AS A RESPONSE TO MORE AMENABLE CLIMATIC CONDITIONS AFTER THE LITTLE ICE AGE, WHICH SEVERELY THINNED THE POPULATION BY AN UNBALANCED NATALITY/MORTALITY RATE (KULLMAN 1986, 2005). PHOTO: 2015-09-12.

(A) **(B)**

FIGURE 3. (A) ISOLATED PINE STAND ON A RIVER BANK IN THE HANDÖLAN VALLEY 690 m a.s.l. (63° 12´N; 12° 24´E). PHOTO: HARRY SMITH 1914-04-12. BY THE EARLY 20TH CENTURY, OLD-GROWTH PINES DOMINATED THE STAND. (B) UP TO THE PRESENT DAY, LOW TREES AND SAPLINGS HAVE CENTRIFUGALLY EXPANDED THE POPULATION. AT THE FRONT, SOME VETERAN PINES HAVE BEEN STORM-FELLED DURING THE PAST FEW YEARS. PHOTO: 2016-02-29.

Up to a limit 4 km to the south of the current forest outposts (Fig. 2 and 3), until the mid-1970s, minor clumps of trees and scattered solitary specimens, some of which were old-growth or moribund, constituted the southern fringe of pine tree distribution (Fig. 4, 5, 6). Subsequent monitoring studies (Kullman 2005, 2014a) have shown that many of these veteran pine

have produced offspring in their nearest circumference, after the 1930s. Certain of these recruits have reached tree-size up to the present day and have over-topped the parent trees. The strict confinement of regeneration close to putative old-growth parent trees is a small-scale equivalent to the recent performance of the closed pine stands, i.e. internal growth and expansion, but virtually no spatial range margin shift of the forest line, as evident also from other studies in northern regions (Holtmeier 2005; Rannow 2013; Hofgaard et al. 2013; Kullman 2015a,b).

(A) (B)

FIGURE 4. (A) SOLITARY VETERAN PINE, PRESUMABLY THE LAST SURVIVOR OF A PRIOR SMALL STAND. PHOTO: 1977-03-14. (B) SINCE THE MID-1970S A COHORT OF YOUNG (60-70 YEARS OLD) TREE-SIZED PINES, TALLER THAN THE OLD-GROWTH PARENT TREE, HAS EMERGED. NORDER TVÄRÅKLUMPEN 695 m a.s.l. PHOTO: 2016-02-29.

(A) (B)

FIGURE 5. (A) MATURE PINE (NO.10), WHICH BY THE MID-1970S WAS THE SOUTHERNMOST TREE-SIZED PINE IN THE HANDÖLAN VALLEY. PHOTO: 1977-02-03. (B) THE PINE WAS BROKEN IN A WINTER STORM 2005/2006. BEFORE ITS DEATH, IT GAVE BIRTH TO A COHORT OF 12 YOUNG SPECIMENS (0.1-1.0 M TALL) WITHIN A CIRCUMFERENCE OF 10 M. NORDER TVÄRÅKLUMPEN, 705 m a.s.l. PHOTO: 2016-02-29.

Nine currently fast-growing solitary trees have become established, with a peak in the 1930s, quite evenly distributed along a stretch, extending 12 km south and 135 m higher upslope of the nearest treeline position hold by the mid-1970s (Kullman & Öberg 2009) (Fig. 7, Table 1).Typically, all these newly emerging trees exist in relatively open habitats in the mountain birch forest, foremost on mires, river banks and in glades with different origins. This process may be seen as a reclamation of territory hold by pine forest during the early-to mid-Holocene until the Medieval Climate Optimum and was finally lost during the subsequent Little Ice Age (Kullman 2013, 2015). Over the relatively cold late 19th and early 20th century, scant pine regeneration took place in the concerned mountain valley as judged from age-witness reports and retrospective age structure analyses (Sernander 1899, 1902; Kullman 1987, 2005, 2015b).

FIGURE 6. SMALL AND SPARSE PINE STAND, CONSISTING OF EIGHT TREES, ESTABLISHED IN OPEN BIRCH FOREST ON THE WEST-FACING BRINK OF THE HANDÖLAN RIVER (MT. METTJEBURRETJAKKE) 705 m a.s.l. THE TREES DEVELOPED FROM SEEDS WHICH GERMINATED DURING THE LATE 1930S TO EARLY 1950S AND POSSIBLY THEY ORIGINATE FROM A DEAD, STILL STANDING VETERAN PINE TO THE RIGHT IN THIS IMAGE. PHOTO: 2013-04-06.

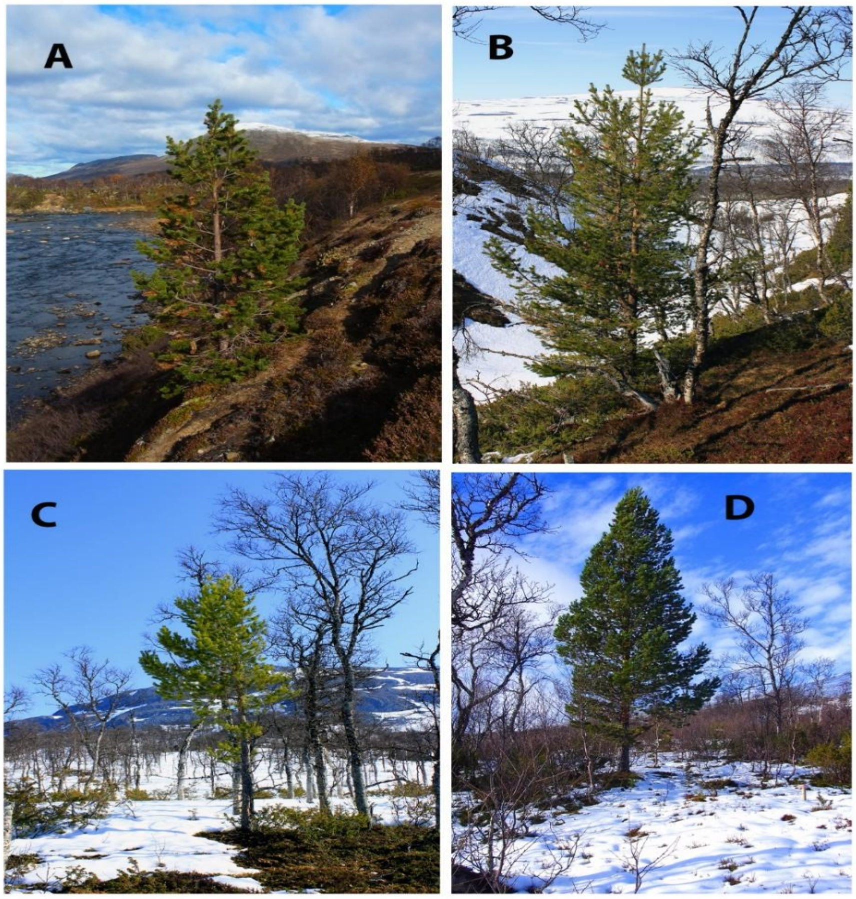

FIG. 7. EXAMPLES OF TREES WHICH AFTER 1973 EXTENDED THE PINE TREE LINE FURTHER SOUTHWARDS IN THE HANDÖLAN VALLEY. PINE NUMBERS AND METADATA REFER TO TABLE 1. A. PINE NO. 2. PHOTO: 2013-09-26. B. PINE NO. 1. PHOTO 2011-04-24. C. PINE NO. 3. PHOTO: 2011-04-22. D. PINE NO.7. PHOTO: 2012-10-20

TABLE 1
POSITIONAL AND INDIVIDUAL CHARACTERISTICS (ARRANGED SOUTH TO NORTH) OF PINES WHICH EXTENDED THE TREELINE SOUTHWARDS AFTER 1973

Pine no.	Position (°N lat.; °E long.)	Altitude (m a.s.l.)	Size (m)	Age (year)
1	63 05 071; 12 25 089	805	3,5	78
2	63 07 593; 12 25 158	830	9	75
3	63 07 972; 12 24 833	770	5	67
4	63 09 023; 12 23 414	740	5	68
5	63 09 179; 12 27 347	745	3.5	40
6	63 09 353; 12 21 015	800	2	25
7	63 10 321;12 21 884	750	8	72
8	63 11 117; 12 22 243	775	2.5	26
9	63 11 607; 12 23643	705	5.0	71
11	63 11 734; 12 23 546	705	dead	
10	63 11 910; 12 23 513	700	dead	

Coincident with tree spread towards the south in the valley during the past four to five decades, scattered saplings have established in open habitats, occasionally even above the birch treeline in mountain slopes on both sides of the valley (Fig. 8). The prospect for these specimens to attain tree size is quite uncertain since many have suffered heavy needle mortality (frost drought) in recent years, which have checked their possibilities to comply with the treeline criteria. On the other hand, tree-sized pines grew at these elevations on the valley slopes in the study area (Mt. Tjallingklumpen and Mt. Laptentjakke) during the warm Medieval period until the late 15th and early 16th century (Kullman 2015b).

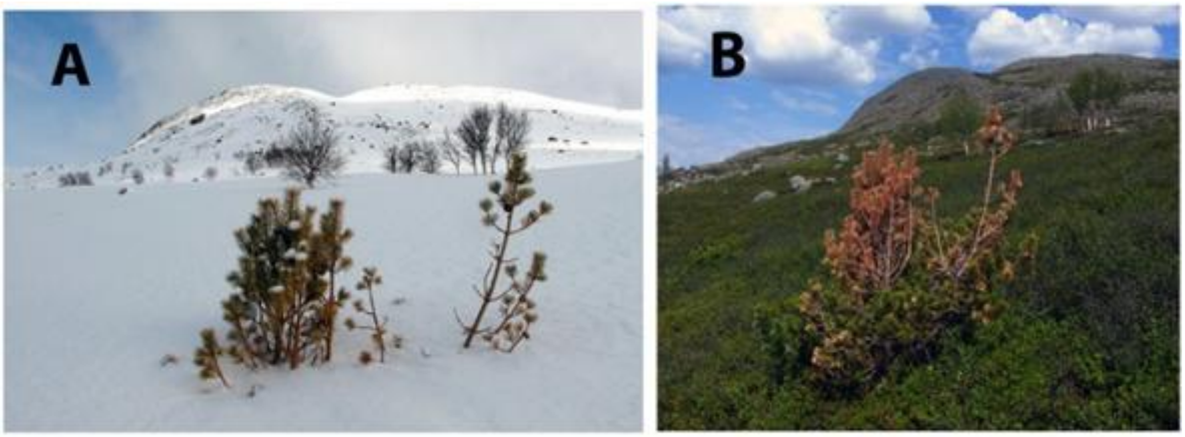

FIGURE 8. YOUNG PINE SAPLING, 1.4 m tall, GROWING EXPOSED ON THE ALPINE TUNDRA, 45 M HIGHER THAN THE LOCAL TREELINE. MT. METTJEBURRETJAKKE, 885 m a.s.l. PHOTO A: 2013-04-07. PHOTO B: 2013-05-31.

The occurrence of scattered well-grown pine trees in the mountain birch forest along a stretch of c. 12 km south of the treeline prevailing in 1973, may hypothetically suggest that much of the valley floor up to this position is currently potential ground for growth of closed pine forest. Strict confinement of newly established trees to gaps or thinnings in the birch forest, indicates that the dense birch forest belt with its lush ground cover, by competition for light and nutrients, constitute the main obstacle for pine to regain its lost territory and to approach equilibrium with current climatic conditions. This contention is further supported by the fact that the pine treeline reaches higher elevations towards the south in the valley (Table 1), where the birch belt is narrower and relatively less dense. This relates to a more open, wind-exposed and snow-poor landscape, which do not support broad and dense belts of birch forest. Prevailing winds blow from the southern sector, as evident from geomorphological structures (Frödin 1956) This circumstance may be a strongly contributing factors in the present respect, reducing the rate of pine forest expansion southwards in the valley.

Historical evidence in support of the pivotal role of the mountain birch forest belt for the reforestation of lost pine forest at high altitudes is provided by the rapid early-Holocene immigration and large-scale spread of pine, during a time when

virtually no distinct birch belt existed (cf. Kullman 2013). Moreover, at this time expansion at the landscape-scale was facilitated since the first pine stands following deglaciation were established on high and early deglaciated nunataks. From these ice-free mountain peaks, seeds and trees were relatively readily spread down slope (Kullman & Kjällgren 2000; Kullman 2008; Carcaillet et al. 2012), i.e. a situation quite different from today. These circumstances indicate that even in a much warmer future climate, pine forest advance may take place very slowly and patchily where dense mountain birch belts prevail and where spread has to take place against prevailing winds and along an extensive elevational gradient.

In addition to southward spread of pine during the past 100 years or so, scattered solitary spruce (*Picea abies*) have expanded the tree line by 30 m altitudinally and about 3 km south of its position during the mid-1970s (Fig. 9). Quite obviously, these trees, like some of the new pines, have benefitted from modest forest clearings made by the Sami people.

FIG. 9. SOLITARY *PICEA ABIES*, WHICH BECAME ESTABLISHED IN THE LATE 1940S, WHERE THE BIRCH FOREST COVER HAD BEEN SUBSTANTIALLY THINNED. MT. TJALLINGKLUMPEN 800 m a.s.l. PHOTO: 2013-09-26

V. CONCLUSION

- Concurrent with climate warming of all seasons over the past 100 years and up to the present day, the forest line of Scots pine (*Pinus sylvestris* L.) has remained positionally static, although substantially densified.
- Since the mid-1970s, the tree line advanced by 135 m in elevation and 12 km southwards in the valley.
- The large spatial separation between the current forest and tree line likely relates to the intervening subalpine birch forest belt.
- Hypothetically, much of today´s subalpine birch forest belongs to a potential pine forest belt.
- Based on current changes and given a warmer future, an analogue to the early and mid-Holocene vegetation structure may evolve. As a main consequence, the birch forest belt may be replaced with a subalpine pine belt.

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